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MOLYBDENUM FORGING PROCESS DEVELOPMENT

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15 September 1962 to 14 June 1963

METALLURGICAL PROCESS BRANCH
MANUFACTURING TECHNOLOGY DIVISION
MATERIALS LABORATORY
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

ASD PROJECT NO. 7-756

A reproducible process for forging thin-section shapes of TZM alloy has been demonstrated. Forgings produced met all contract requirements including surface finish (125 RMS) and web thickness (.130 inch max.).

(Prepared under Contract AF 33(600)-41419 by the Westinghouse Electric Corporation, Materials Manufacturing Division, Blairsville, Pennsylvania, A. W. Goldenstein)

NOTICES

FOREWORD

This Interim Technical Progress Report covers the work performed under Contract AF 33(600)-41419 from September 15, 1962 to June 14, 1963. It is published for technical information only and does not necessarily represent the recommendations, conclusions, or approval of the Air Force.

This contract with the Westinghouse Materials Manufacturing Division, Blairsville, Pennsylvania, was initiated under Materials Laboratory Project 7-756 "Molybdenum Forging Process Development". It is administered under the direction of Mr. L. C. Polley, Project Engineer, Metallurgical Processes Branch, Manufacturing Technology Division.

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ABSTRACT SUMMARY
Interim Technical
Progress Report No. 9

ASD Interim Report 7-756(IX)
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by

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Blairsville, Pa.

A reproducible process for forging thin-section shapes of TZM alloy has been demonstrated. Forgings produced met all contract requirements including surface finish (125 RMS) and web thickness (.130 inch max.).

An approved modification of the original flame-shield design incorporating one heavy central rib instead of two thin ribs and appropriate changes in forging dies was made.

The effects of forging and annealing temperatures, methods of forming blanks, trimming, the number of forging blows per heat, in-process and final conditioning, positioning of the forging blank, and cleanliness were investigated in relationship to forgeability and final quality. Some of the above would be required to produce any new forging, some were performed in earlier phases but with less emphasis on forgeability, some might be classified as "shop practice" or die design but all of it was essential to successful production of the desired forging.

Some essential features of the developed process are (1) rapid transfer from furnace to die, (2) restricting time in forging dies by limiting forging to only a few rapid, hard blows per heat (one blow per heat for this forging), (3) repeated reheats, (4) in-process anneals, and (5) careful in-process conditioning.

Approval of the detailed process which is presented and permission to proceed with the pilot production run is requested.

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I. INTRODUCTION

This is the ninth Interim Technical Report on Contract No. AF 33(600)-41419. Work on this contract is directed towards the development of an economical, reliable process for the production of closed-die forgings.

Phase I was an evaluation of the state-of-the-art. A procedure for direct hot-work forging of ingots was developed in Phase II. Work in Phase III was directed towards evaluating process variables, developing in-process control procedures, and arriving at the optimum method for producing high quality closed-die forgings incorporating the direct hot-work forging procedures developed in Phase II.

In Phase IV the effectiveness of the procedures developed earlier will be evaluated by producing test forgings. Initial effort was directed towards selecting or designing a replacement for the universal or contour forging. A major modification of this replacement forging was found necessary in order to produce a satisfactory forging. The modification has been approved and work on the ammended Phase IV program is in progress.

II. SUMMARY

A reproducible process for forging thin-section TZM shapes meeting contract requirements has been developed. The experimental work, the recommended process, and results of evaluation of final test forgings are presented. An approved modification of the original flame-shield design incorporating one heavy central rib instead of two thin ribs and appropriate changes in forging dies was made.

The effects of forging and annealing temperatures, methods of forming blanks, trimming, the number of forging blows per heat, in-process and final conditioning, positioning of the forging blank, and cleanliness were investigated in relationship to forgeability and final quality. Some of the above would be required to produce any new forging, some were performed in earlier phases but with less emphasis on forgeability, some might be classified as "shop practice" or die design but all of it was essential to successful production of the desired forging.

Some essential features of the developed process are (1) rapid transfer from furnace to die, (2) restricting time in forging dies for limiting forging to only a few rapid, hard blows per heat (one blow per heat for this forging), (3) repeated reheats, (4) in-process anneals, and (5) careful in-process conditioning.

Approval of the detailed process which is presented and permission to proceed with the pilot production run is requested.

III. EXPERIMENTAL WORK

A. General

A certain amount of experimentation was performed with the modified forging design prior to approval of the ammended program. Much of this work and the work subsequent to approval might be properly labeled as shop practice or die design. However, since it was essential, details are included.

Upsetting one end of a bar to gather enough metal to form the flared ribs was initially planned in forming blanks. Upsetting four bars, B-1 through B-4, produced one good blank (B-4) which was subsequently blocked and finished to produce the first forging.

A split die or a more severe taper in the hole used to contain the bar during upsetting could have overcome the above problem. However, another approach which appeared simpler and more direct and economical was considered. All but about a half-inch at the center of a larger diameter bar was swaged to the required shank diameter. The bar was then cut through the larger unswaged center section to form two blanks.

Four forgings, designated C-1 through C-4 were produced from enough bar stock for four blanks which proved the practicality of the swage forging procedure. These forgings were similar to the first forging B-4, i.e., they did not fill completely, had a rough surface, had an oversize web, and contained a prominent defect at the base of the thin flared ribs.

The next forgings, D-1 and D-2, were produced singly. Lubricant was used more discriminatingly to promote proper metal flow; they were conditioned and trimmed at intermediate stages, trimming being done so as to allow the metal to flow away from the backside of the flared rib where the seam or crack defect had formed on the first forgings. The results were partially successful. However, it became apparent that varying geometry of the rough forged blank and die design were in part responsible for this difficulty.

Forgings D-3 and D-4 were block forged at a higher temperature (1750°C) to find whether increased metal plasticity at this temperature would result in an improvement. The defect at the base of the thin ribs was not eliminated and surface condition was worse.

Die changes consisting of blending the flared rib cavities gradually out into the flash pan and radiusing the fillets on either side of these cavities more generously were made and forgings E-1 and E-2 were produced. These die changes resulted in only a minor change in the finished dimensions. These changes plus the other procedures above described reduced this defect to where it is at most a surface blemish which requires no more than a few minutes with a hand tool to eliminate.

When the ammended Phase IV Work Program was approved, more material was ordered and, when received, processing and evaluation was begun. An initial group of four blanks (F3 B&C and F8 B&C) were produced without incident. However, longitudinal cracks appeared in the

plate sections of these forgings during blocking. Finish forging the worst of these two after a recrystallization anneal plus evaluation work tended to confirm that a portion, at least, of this material wasn't completely recrystallized as-received.

A second group of four forgings (F3 A&D and F8 A&D) were produced. These were of a good quality except for surface smoothness and a small crack on one side of F3 D.

Steps taken to improve surface were to (1) repolish die cavities, (2) acid pickle blocked forgings, (3) more carefully condition blocked forgings, (4) anneal at a lower temperature prior to finish forging, and (5) prepare a tray to catch forgings in the event they bounce from the die after being struck. Surfaces of forgings produced after incorporating the above into the process had an average smoothness of less than 120 RMS as sandblasted except in a few areas which could be easily improved in post forging operations.

Die cleanliness and a still more sparing use of lubricant was indicated, however, since it was evident that dirt particles were present in the thin rib sections of the die cavity on two forgings and since brush marks from applying lubricant appeared to have been transmitted to the surface of one forging. Greater care here plus the fact that in the production run the hydrogen atmosphere heating furnace will be moved closer to the hammer which will decrease the average time from the furnace to the die from about 8 seconds to 4 to 5 seconds, will result in further improvement.

The last group of forgings are considered to be of a high enough quality to be presented as proof of the process and they, with the detailed process used in producing them, are being submitted for approval prior to making the pilot production run.

B. Process Variables

1. Forging Temperature

When difficulties were encountered with the flame shield as originally designed for the contract, attempts were made to overcome them by increasing the work piece temperature. These initial results were inconclusive.

Blocking of the first successful forging of the modified design (a single heavy central rib) was performed at 1750°C. Finish forging was at a lower temperature (1510°C) due to dimensional limitations of the high temperature furnace. The resultant forging had a coarse, non-uniform structure, see Figure No. 1.

The next forgings (C-1 through C-4) were blocked and finished at a nominal temperature of 1525°C. The structure of the latter forgings was much finer and more uniform, see Figure No. 2. Die fill was equivalent to the first forging and the surface was superior.

Block forging of two more blanks, D-3 and D-4, was later performed at 1750°C to determine whether the defect which appeared at the base of the thin ribs of the first forgings would be reduced in severity. No improvement was noted.

In general, increasing forging temperature (within limits) would be expected to improve forgeability. However, other factors must be considered.

Grain coarsening decreases forgeability. In TZM, the temperature at which this occurs is shifted upwards relative to unalloyed molybdenum due to the restraint imposed by the carbide phase. The extent of this shift has not been determined; however, forging B-4 (Figure No. 1) block forged at 1750°C has a coarse non-uniform structure. Such a structure is undesirable with respect to both subsequent forgeability and final properties. In retrospect it appears that direct hot-work forging of ingots, as per earlier phases of this contract, would of itself not produce a fine grained and, therefore, highly forgeable material.

Exposure to increasing temperatures results in increasing solution of molybdenum and Ti(Zr) carbides. This might be considered desirable in early conversion stages to promote homogeneity and to produce a refined and dispersed carbide on reprecipitation. Solution of these carbides, or a portion of them, might also be found desirable if interest is primarily in high elevated temperature strength; however, decreased forgeability should be expected if subsequent warm working operations are performed due to strain-induced precipitation. Also, a fine highly dispersed carbide or a supersaturated matrix phase would be expected to affect the ductile-brittle transition temperature adversely.

The rate of deterioration of the forging dies increased and the surface condition of forgings became poorer with increasing forging temperatures.

Forging temperatures are thus a compromise. The forgeability of TZM is good at 1500°C provided it hasn't been previously "overheated". At this temperature a degree of work hardening put into the structure can be retained (as per hardness checks) provided exposure to this temperature is not prolonged. Accordingly, this temperature was ultimately decided upon. Other somewhat more devious methods, which will be discussed later, were used to increase metal flow or "apparent plasticity".

Initially swage-forging was begun at 1700°C to 1750°C. However, it was found to be unnecessary and this operation is carried out at a starting and reheating temperature of 1500°C to 1525°C.

2. Annealing Temperature

The first successful forging produced was block-forged at 1750°C. It was finish forged at 1500°C to 1525°C. Getting the plate section of this forging down to size proved difficult. Ultimately, it was given an intermediate anneal. A molybdenum sintering furnace at 1750°C was used. A hardness drop from about 100 R_b to 84 R_b resulted and the plate section was reduced about another 0.010" in thickness after additional forging drops in the finish die. The section was still oversize, however, and the hardness again increased to about 100 R_b. The small reduction, the

relatively high forging temperature, and the increase in hardness were suggestive of the strain-induced precipitation phenomenon reported elsewhere.* An equal difficulty was encountered in trying to bring forgings C-1 through C-4 and D-1 and D-2 to size.

Forgings E-1 and E-2, annealed at 1700°C, 50° lower than the previous forgings, came closer to meeting contract requirements. A direct comparison cannot be made; however, the dies had also been modified and this might have contributed to the improvement.

Enough information was obtained to point out, in a qualitative way at least, the direction to go with respect to annealing temperatures. A 1650°C anneal was chosen somewhat arbitrarily prior to finish forging. Higher temperatures were to be avoided at this point. Some lower temperature might have served as well, indeed a prolonged "aging treatment" at the forging temperature or slightly above it might in greater improvements in forgeability. A prolonged anneal, however, would not fit into practical requirements for a forging process.

A higher temperature, 1700°C, was used for annealing at an earlier stage (subsequent to extruding) to insure complete recrystallization and to affect some degree of refinement of the carbide phase through solution and reprecipitation.

* W. Chang, A Study of the Influence of Heat Treatment on Microstructure and Properties of Refractory Alloys, Contract AF 33(616)-7125.

3. <u>Extrusion Temperature</u>

Starting stock was a nominal four-inch diameter extruded and recrystallized billet. Diameter prior to extrusion was 10-7/8 inches. The initial extrusion temperature is not known. Since the material received a 1650°C anneal subsequent to extrusion, however, the extrusion temperature was probably not above this.

The first stage in the process as outlined in this report is to re-extrude the starting stock. The temperature for this operation in producing the test run forgings was 1590°C (1575°C to 1600°C specified).

The main purpose of the re-extrusion operation was to convert the material to more manageable dimensions and, therefore, little was done other than to be sure the temperature was such that this step could be accomplished without difficulty.

Possibly the thermal and mechanical steps (extrusion and high temperature anneal) might have been combined to advantage into one step at this stage. However, more attention here would have detracted from the primary objective of producing satisfactory forgings.

4. <u>Producing Forging Blanks</u>

Initially it was planned to form forging blanks by upsetting one end of a bar to gather enough metal to form the flared ribs. This was in line with the procedure planned for the original design.

A die containing a tapered hole with an average diameter of 1-3/4 inches was available. A heated length of TZM bar was to be placed into this hole and the protruding end upset forged.

The forging operation was accomplished readily, only 2 to 3 quick blows being required. Extracting the bar from the die was the troublesome operation. Polishing out the tapered hole and the generous use of lubricant was effective but the operation was still too border-line to be considered in the process without going to a split die or at least a die with a more highly tapered hole.

Swage forging a larger diameter bar to produce the same configuration obtained by the upsetting operation appeared to be a more direct solution. Three inches of each end of a 6-1/2-inch length of 3-inch diameter bar were swage-forged to a 1-3/4-inch diameter using stepped dies. Three to four heats were required to bring each end down to size. This operation did not proceed quite as easily as desired due to the slipperyness and stiffness of TZM and a rough looking blank resulted. The use of a stop to position the bar at the proper distance into the die at the start and maintaining tooling in good condition minimized difficulties however.

A swage-forged blank and a partially blocked forging produced from such a blank were sectioned and evaluated. The macro-

structure appeared fine and uniform. The micro-examination indicated that if anything the structure of the swage-forged end of the blank was slightly coarser. The grains in this end were slightly elongated compared with the other end revealing the difference in work. Hardness checks on sections of the swage-forged blanks, likewise, revealed difference in work. Hardness trends were reversed in the partially blocked forging, however, indicating that the differences present earlier are more than compensated for. The 1650°C anneal in the procedure prior to finish forging would also tend to reduce differences in structure and properties due to unequal degrees of work in earlier operations.

Macro structures of the swage-forged blank and partially blocked forging are presented in Figure Nos. 3 and 4.

A variability in fill occurred in the first forgings produced. Blank geometry was found to be a contributing factor. An improvement in die fill was obtained by making the small diameter end of the blank wedge-shaped so that it could fit into the heavy rib section of the die. This shape is produced by flattening the end on a forge hammer and then touching it up by grinding.

5. <u>Trimming</u>

An excess of metal is required to produce the flame shield forging with the present set-up. The flash pan adjacent to

the thin rib cavities must be fairly well filled if these rib cavities are to fill. A more elaborate blank shape, a redesigned die system incorporating mating upper and lower dies, eliminating or reducing the flash pan in the above mentioned area, and a procedure utilizing three (or four) sets of dies or die cavities would improve yield. Experimentation along the above lines would delay attainment of the primary objective of the project, however, and is, therefore not considered justifiable.

Trimming is done on partially blocked forgings, prior to finish forging, and of course, subsequent to finish forging.

When trimming at the intermediate stages, it was found advantageous to retain about one half-inch of flash at the front of the thin flared ribs to limit subsequent metal flow in this direction. It was also found advantageous to trim back into the forging behind these ribs to promote metal flow away from or at least parallel to them rather than under them. This aided in the elimination of the fold, or seam type defect found at their base on the first forgings.

Partially blocked forgings are trimmed back 3/4 inches into the plate section of the forging to within 3/4 inches of the backside of the thin ribs at which point the direction of cut is changed to where it is at right angles to these ribs and is extended into the flash pan. The forgings are

trimmed similarly prior to finishing except that the amount of metal removed from the plate section is reduced to 1/2-inch. A band saw is used for these operations.

The variations in size and shape of the rough forged blank which previously contributed to variations in finished quality are effectively neutralized by the trimming operations.

6. Lubricants

Spray-coated Dow-Corning 7052 glass was used as a lubricant for extrusion.

In earlier phases it was reported that a molybdenum disulphide type lubricant was most effective for forging work.

Experimentation with lubricants during this phase has been limited to trying to promote metal flow into the more inaccessible parts of the die cavity by its selective application. Results were not conclusive. In view of the slipperyness of hot molybdenum preferential metal flow might be more easily obtained by actually increasing friction in certain areas instead of attempting to decrease it in other areas. Surface finish would very likely suffer.

It has been found that the over-generous use of molybdenum disulphide, or an uneven application of it, can contribute to a poor surface condition. This is more or less contradictory

to earlier information where its use was said to have resulted in an improved surface. Brush marks from the application of this lubricant to the die in some cases actually were transmitted to forgings. It is also suspected that it can contribute to surface contamination. For these reasons, sparing application of lubricant is recommended in finishing operations.

7. Number of Forging Blows per Heat

In the earlier phases of the project and initially in Phase IV, actual forging operations were similar to standard practice for steel forging, i.e. heated metal was placed under the hammer and forged with repeated blows until a minimum forging temperature was reached or until it was too cold and stiff for further deformation. This worked well enough for rough work with relatively large pieces or thick sections. However, the high hot strength of TZM, the high forging temperatures and high heat conductivity with the consequent more rapid heat loss make production of ribbed thin sectioned TZM forgings difficult.

Little in the way of experimentation and observation was required to discover that there was less sticking in the die, better die fill, less die deterioration and an improved quality resulted if the work piece was transferred from the furnace to the die, given one (or two) hard forging

blows, and then transferred back into the furnace, all steps being carried out as quickly as practical. This is somewhat of an extrapolation of the rule of thumb used in forging molybdenum to "hit it hard and fast, to get it moving and to keep it moving".

The greatest amount of metal flow in thin sections occurs on the first forging blow. The high heat conductivity and consequent rapid chilling make succeeding blows, without a reheat, of little value.

The above procedure combined with one heating furnace may not be considered economical. With more heating equipment, however, one group of forgings could be worked on and transferred one at a time to a reheat furnace while another group was being reheated. This would be both practical and economical and is, in fact, analogous to the sequence of operations which has been used in the production swaging of sintered tungsten and molybdenum wire bars.

The procedure of transferring the work piece from the furnace to the die for one quick, hard forging blow and then back to the furnace for reheat has been incorporated in the process recommended for the pilot production run.

8. In-Process Conditioning

Conditioning in earlier phases of the contract consisted of machining surfaces of forged billets, sandblasting or roto-

blasting, of spot conditioning by grinding with a carbide burr, of removing contamination by working over the entire surface with a carbide burr at intermediate stages and, for a time, of pickling.

In Phase IV extruded bars have been sandblasted or roto-blasted, nose and tails have been cut off, and localized defects removed by grinding. This amount of conditioning appears to have been sufficient at this stage.

Localized defects, rough spots, and sharp corners or edges in swage-forged blanks have been eliminated by grinding. Blanks have been sandblasted or roto-blasted prior to blocking. Greater care is required as the work piece approaches final dimensions so that a satisfactory finish is obtained, therefore, an acid pickling operation has also been placed in the process at this stage.

Trimming operations are performed on partially blocked forgings. Spot conditioning of obvious defects is also carried out at this time.

After the completely blocked forging has been trimmed, it is roto-blasted, pickled and all surfaces conditioned with an air driven hand tool and a carbide burr. The pickling solution consists of 15% 42° Baume HNO_3, 2% HF, and the balance water. Throughout all these conditioning steps great care is important to insure good final finish.

9. Post-Forge Conditioning

Flash from finished forgings is removed with a band saw. The forgings are then sandblasted and inspected. Any surface blemishes are removed by hand operations. (In some cases, for example, a trace of the defect at the base of the thin, flared ribs was evident. However, a few minutes with a small hand grinder can eliminate this.) Edges of the forgings are touched up on a belt sander to remove any remaining traces of flash and to bring length and width dimensions to within requirements. The forgings are then again sandblasted and considered completed.

10. Cleanliness

Forgings occasionally bounced from the die cavity on being struck resulting in contamination by dirt and scale. A tray constructed to fit around the bottom forging die to catch a forging in such an event eliminated this cause of poor surface.

Surface contamination by iron picked up during roto-blasting, swage-forging, or other forging operations could also produce a poor surface. A pickling operation aids in removal of such contamination and has been incorporated into the process.

The use of the molybdenum disulphide lubricant, recommended in earlier phases, might result in a better surface and decreased friction in certain temperature ranges. It is suspected that

overly generous use can cause poor surface through contamination and build-up in the die cavity; therefore, it will be used sparingly, especially in finish-forging.

The die cavity is cleaned with a rotary wire brush between heats. Dirt in more inaccessible regions in the die cavity has been blown out with an air hose. This has not proved adequate and a brush suitable for use in these areas was acquired and made use of.

An occasional more thorough cleaning or repolishing is required. The frequency with which this operation has to be repeated has not been determined. During experimental work the finishing die had been repolished several times, however, it also received more abuse during this time than is anticipated in the recommended process. An operation as described should be anticipated in the forging process and will be performed if required.

11. Recrystallization Temperature

Recrystallization temperature is a function of percent reduction, temperature of reduction, time at temperature, and for TZM (as per earlier work on this project and other recent work) of prior work, work temperature or solution annealing temperature.

Molybdenum and tungsten are to some degree peculiar (at least in sheet form) in that although initiation of

recrystallization might be observed at a given temperature, either a higher temperature (as much as 200°C higher) or very long times are required if the reaction is to proceed to completion. TZM would be expected to act similarly. This, plus dispersion, size, and perhaps shape of the carbide phase which affect recrystallization temperature as noted in the previous paragraph complicate recrystallization behavior of TZM.

Detailed recrystallization studies have not been made and are not scheduled to be made. The effectiveness of in-process anneals is judged primarily by their results on forgeability.

The forging temperature recommended is close to and for some conditions well above the temperature at which recrystallization can initiate. This might account for anomalies such as the fact that the small end of the sectioned swage-forged blank appeared to have a slightly coarser structure than the large end. Also, it appears likely that the hardness increases observed on forging at these temperatures could be caused by a process, or processes, other than simple work hardening.

12. <u>Positioning Blanks in the Blocking Die</u>

It has been found that if the large end of the blank is not placed well over the thin rib sections of the die cavity, these sections will not fill well. Accordingly, the blank

is positioned carefully prior to the first forging blow and then given only a light blow. This serves to locate the blank properly and is, therefore, essential.

13. Die Wear

During the course of experimentation deterioration of the finish in the forging die cavities was observed. These surfaces were repolished as required.

When procedures were refined to the point where dimensions became one of the major remaining concerns, the thickness of the plate section of forgings (E-1 and E-2) were found to vary by 0.010" to 0.012" from the edge to the center, the center next to the heavy rib section being thicker.

A depth micrometer indicated the depth in the plate section of the die cavity at the center immediately behind the thin flared ribs to be about 0.006" deeper than at the edge on the other end of the forging. A difference in depth of up to 0.005" was found between central points and corr-esponding edge points at right angles to the heavy central rib. These differences correspond to figures of about 0.003" and 0.002" respectively, which were obtained at the time the dies were modified to produce a forging with one heavy central rib. Thus a differential in wear of about 0.003" to 0.004" occurred.

The balance of the difference in thickness of the plate section of the forgings presumably is due to elastic

deformation of the dies when the work piece is struck and can be compensated for if need be.

14. <u>Transfer Time</u>

Transfer time from furnace to die was 7 to 8 seconds during experimental work.

The furnace will be moved closer to the hammer for the pilot production run which will reduce transfer time by about one-half. Fewer forging blows to finish, a better surface, and a more rapid completion of the pilot run is anticipated as a result.

C. <u>Die Modifications</u>

The major die modification consisted of removing the projection within the central rib cavity to result in a forging with a single heavy central rib rather than two thin central ribs. The resultant heavy rib portion of the blocking die cavity was deepened (0.031") and the bottom rounded slightly to increase the amount of metal in this part of blocked forgings and to result in a better filled out finish forging.

The fillet between the plate section and the flared ribs was made more generous to counteract the tendency towards formation of a wrinkle, crease, or crack at this location.

The flared rib portion of both the blocking and finishing die cavities was extended out and blended into the flash pan. These

ribs are tapered down to a height of 1/4" at the edge of the forging compared to the zero height in the original drawing. The extensions of these ribs in the flash pan will not otherwise change the forging geometry since this portion will be removed on trimming.

IV. TEST FORGINGS

A. Quantity

The nine finished and two unfinished forgings produced prior to approval of the amended work program and the first eight produced afterwards were made in the process of optimizing production procedures for the modified flame shield. Die modifications were also made at this time. In addition, forging temperature, anneals, annealing temperatures, trimming, and in-process conditioning procedures were varied. Evaluation of these forgings was primarily to determine the effectiveness of changes made.

Procedures essentially as recommended in the next section were used in producing only the last eight forgings. Even subsequent to these, a number of minor variations are recommended. These changes are made to reduce forging time and possible causes of surface roughness, however, and will not affect mechanical properties. These changes, most of which are also discussed under the section "Variables" are listed below:

1. Moving the heating furnace closer to the forging hammer
2. Resurfacing the flat top die
3. Using lubricant more sparingly during finish forging
4. Obtaining and using a rotary wire brush which will fit into the more inaccessible portion of the die cavities

Since the recommended process, except as noted above, was used in producing only the last eight forgings, only these should be considered for purposes of evaluating quality and the process.

B. Evaluation

Evaluation of the last eight forgings consisted of dimensioning the finished forgings, checking surface smoothness, determining the extent of surface, or other types of defects, and noting any other variation in condition.

Finished weight is 4 pounds 4 ounces.

The defect at the base of the flared thin rib was reduced to where it was at most a small crease at the very end even without conditioning.

Surface roughness such as the imprint of the brush marks from application of lubricant or due to the upper flat die (which is also used for general forging work) was present to some extent on all of these forgings. The changes tabulated in the preceding section are calculated to overcome this.

Evaluation is summarized in the following table.

Table No. I

Forging Number	Surface finish Rib-Side (RMS)		Dimensions (inches)					
			Plate Thickness (ave.)*		Heavy Rib Height		Thin Rib Thickness **	
	Min.	Max.	Edge	Center	Front	Back	Edge	Center
F1-C	85	120	0.124	0.133	1.247	1.255	0.133	0.187
F1-D	90	140	0.123	0.132	-----	1.250	0.132	0.189
F5-C	100	125	0.119	0.128	1.245	1.250	0.133	0.188
F6-A	100	175	0.121	0.130	1.248	1.252	0.134	0.189
F6-B	110	130	0.122	0.131	1.247	1.249	0.134	0.188
F6-C	110	150	0.120	0.130	-----	1.247	-----	-----
F7-A	100	140	0.122	0.131	1.243	1.249	0.133	0.189
F7-D	90	125	0.122	0.131	1.247	1.252	-----	-----

* Individual readings were within plus or minus 0.004" of the averages. These variations are attributed to variation in die depth and due to "elastic deformation" of the die which are discussed in the text of the report.

** The increasing thickness of these ribs towards the center of the forging and the draft angle make the obtaining of reproducible readings difficult.

V. THE PROCESS

A. Starting Material

1. Nominally 4" diameter extruded and recrystallized billet.

2. Justification for use - an off-the-shelf item; therefore, its use saves time and money.

3. Metallurgically starting diameter of wrought material isn't too important since a great deal more work will be put into it.

4. Specification suppliers, example: Climax CMX-FB-TZM-1.

B. Evaluation

1. Chemistry

2. Macros

3. Micros

4. Ultrasonic - checked by supplier only

5. Properties - non-required on as-received material.

C. Processing

1. Re-extrude to 3" diameter bar.

2. Condition extrusions

a. Roto-blast

b. Remove small defects by grinding; large defects by sectioning

3. Recrystallization anneal - 1700°C - 1 hour

4. Forming forging blanks

a. First step - cut extruded bars into 6-1/2" lengths; swage forge 3" of each end of 6-1/2" lengths to 1-3/4" dia. at 1525°C, two to three re-heats required for each end

b. Second step - cut swage-forged bar in half to form 2 blanks; flatten heavy end of blank to 1-3/4" thick; cut end of shank or stem wedge shaped in order to get better fill at the back end of the heavy rib; and spot condition as required and acid pickle

5. Block forging

   a. Forging temperature, 1525°C

   b. Furnace H_2 atmosphere, moly element, resistance

   c. Initial heating time, 25-30 min.

   d. Reheat time - 5 min.

   e. One forging blow per heat

   f. First drop - light positioning blow; blank positioned by locating heavy (knob end) end over flared rib portion of die cavity

   g. Succeeding drops (8-10 required) - 5 minute reheats between drops; 4-5 seconds time lapse from time the forging is taken from furnace until it is struck (furnace located adjacent to hammer); and a total of 25 seconds until it is back in furnace

   h. Block forging interrupted after about the fifth blow to trim off excess metal

   i. Criterion for completion of blocking is die-to-die contact

6. Conditioning blocked forging

   a. Roto-blast all surfaces

b. Trim - flash is removed except for a half-inch at the front of the forging adjacent to the flared ribs; excess metal is trimmed from the plate section behind the flared ribs to promote metal flow away from the ribs rather than parallel to or under them

c. Condition entire surface - acid pickle; and, grind off any contamination remaining after acid pickling and remove any defects with a small hand-operated air motor and a carbide burr

7. Anneal

a. 1650°C - 1 hour - the anneal and annealing temperature are intended to recrystallize taking a minimum of the Ti (Zr) carbide back into solution to avoid strain-aging on subsequent operations

b. To improve forgeability

c. To improve surface

8. Finish forging

a. Procedures and temperatures are the same as for the blocking operation except that forging is not interrupted for trimming

b. About 6 to 7 blows are required to finish

9. Conditioning

a. Trim

b. Remove any surface defects

c. Sand blast

D. Inspection

1. Check dimensions

2. Check for defects

   a. Visually

   b. Dye-penetrant or zyglo

3. Surface smoothness

E. Rework Operation

1. If any forging are oversize, one or two additional drops will be given to them

2. Conditioning and inspection operations will then be repeated

F. Testing - as per amended work program

VI. CONCLUSIONS AND RECOMMENDATIONS

The first part of the ammended Phase IV work program has been satisfactorily concluded.

It is recommended that the process presented in the previous section be approved and that permission to proceed with the pilot production run be granted.

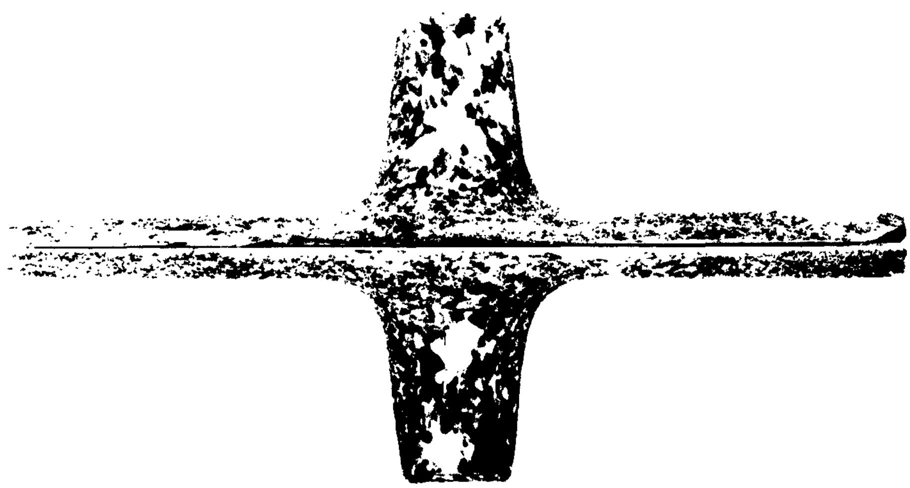

Figure 1 - Macrostructure of forging B-4 after final forging. Blocked at 1750°C; finished at 1525°C. Approx. 1X

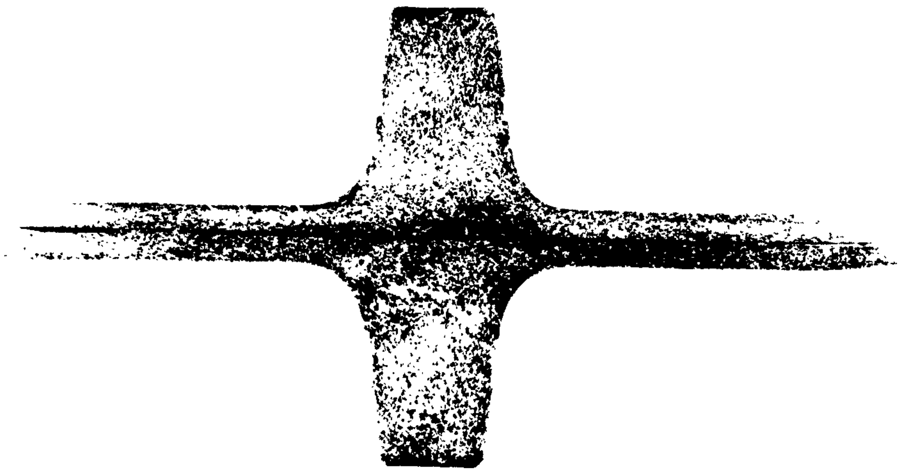

Figure 2 - Macrostructure of forgings C-3 and C-4 after final forging. Blocked and finished at 1525°C. Lower forging (C-4) annealed at 1750°C for 1 hour during final forging. Upper forging (C-3) no anneal. Approx. 1X

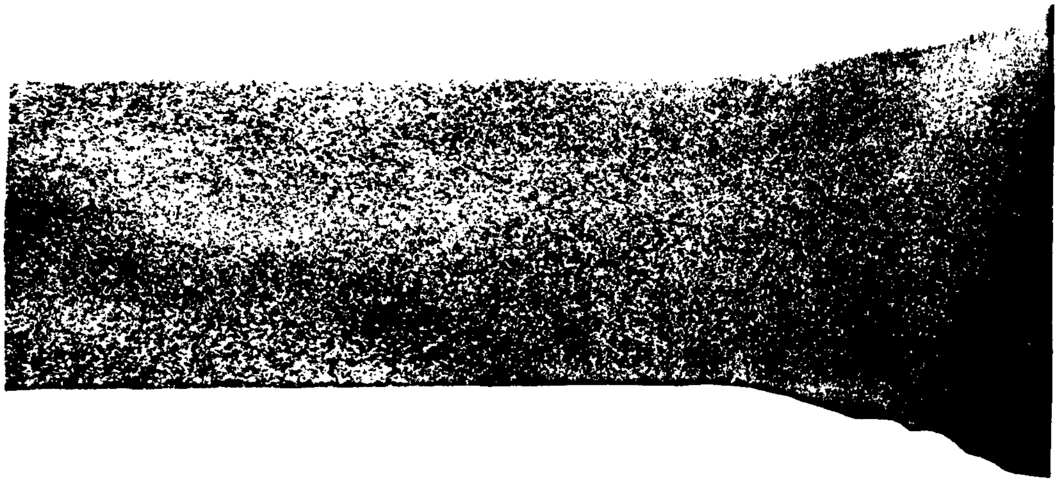

Figure 3 - Macroetched cross-section of swage-forged blank prior to flattening large end. Rockwell "B" hardness: 103 at small end; 85 at large end. No evidence of deleterious flow pattern or grain structure. Approx. 1X

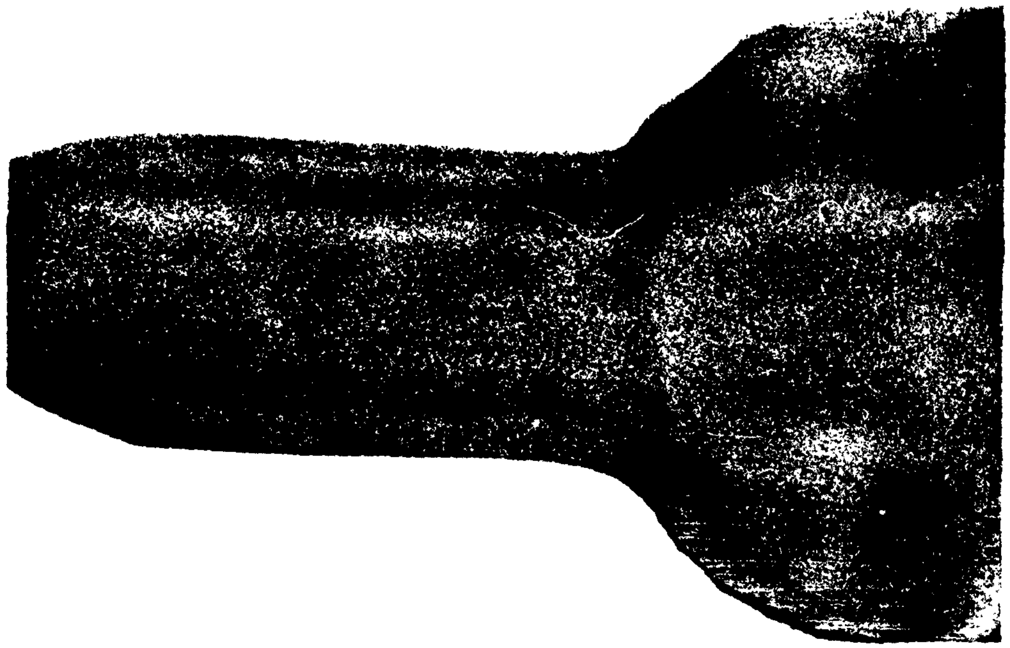

Figure 4 - Macrostructure of a partially blocked forging. Large end of a blank as shown in Figure 3 has been flattened and blank has been given a few drops in blocking die prior to sectioning in horizontal plane just below ribs. Note uniformity of structure and hardness (R_b 102 small end; R_b 103 large end). Approx. 1X

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